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RESEARCH MEMORANDUM

A RELATION OF WIND SHEAR AND INSOLATION TO THE TURBULENCE ENCOUNTERED BY AN AIRPLANE IN CLEAR-AIR FLIGHT AT LOW ALTITUDES

By James K. Thompson

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

The observed gust experience of an airplane and information on the associated meteorological conditions are utilized to obtain a simple empirical relation for estimating the intensity of turbulence in the earth's friction layer. The data were obtained from 23 flights by an airplane operating in clear air at 1500 feet altitude above the average elevation of a given course near Wilmington, Ohio. Coefficients of correlation between a meteorological quantity and the effective gust velocities equalled or exceeded on the average of once in distances of 1 and 10 miles for each flight were 0.88 and 0.84, respectively. On the basis of these results, the meteorological quantity may be expected to yield reliable estimates of the gust experience of an airplane operating under conditions similar to those of the test data. The applicability of this relation, when applied to regions having different topographical characteristics or when extended to other values of gust intensity, however, has not been established.

INTRODUCTION

One of the problems of aviation meteorology is the development of methods for predicting the turbulence encountered by an airplane on a given flight. The nature of physical processes in the free atmosphere, however, are complicated and, although some progress has been made in connection with the prediction of thunderstorm turbulence (reference 1), little progress has been made in connection with the prediction of other forms of turbulence. Of the other forms of turbulence, the turbulence encountered by an airplane while operating in clear air at low altitudes is of importance because of its connection with problems relating to fatigue, airplane performance, and passenger comfort. Although some efforts have been made to develop methods for predicting this form of turbulence (reference 2), no practical method has as yet been developed for predicting the intensity of turbulence encountered by an airplane while operating in clear air at low altitude.

In connection with a loads investigation with jet-propelled airplanes (reference 3) an opportunity was had to study the relation between meteorological variables and the turbulence encountered by an airplane while operating in clear air at a low altitude. The meteorological quantities generally associated with turbulence - such as lapse rate, wind velocity, wind shear, insolation, and Richardson's number - were obtained and examined as a possible measure of the turbulence. Although none of the parameters appeared to provide a consistent measure of the turbulence, the average wind shear between the anemometer and the gradient wind levels did provide a relatively consistent measure of turbulence during a given season. This result suggested that large variations in the intensity of solar heating should be included to form a relation independent of season. A subsequent examination of the applicability of various combinations of the average wind-shear and solar-heating parameters indicated that the intensity of turbulence encountered by the airplane was closely related to the product of average wind shear and total daily solar radiation. Although the relation obtained might possibly be of some limited value as a forecasting tool, the methods of evaluation and the results obtained are presented herein as a preliminary result in the study of relations between low-altitude clear-air turbulence and meteorological variables.

SCOPE OF DATA

The low-altitude clear-air flights for which both meteorological and gust data were available were made over a specific course approximately fifty miles in length near Wilmington, Ohio, during September to December 1948, and May 1949 (reference 3). Each of the flights consisted of a survey between 10:00 a. m. and 4:00 p. m. Eastern Standard Time of the gustiness encountered by airplanes when flown 1500 feet above the surface (2500 feet mean sea level) for a total of 6 to 8 traverses over the course. About two-thirds of the flights were made between 12:00 a.m. and 3:00 p.m. Eastern Standard Time.

The meteorological observations were made available by the All Weather Flying Division of the U. S. Air Force at Clinton County Air Force Base, Wilmington, Ohio. The observations consist of data from the hourly surface observations, continuous records of surface wind direction and velocity, and the 10:00 a. m. and 4:00 p. m. Eastern Standard Time rawinsonde ascents. The rawinsonde data consist of vertical histories of temperature, humidity, pressure altitude, and wind direction and velocity.

Instruments were not locally available for measuring solar radiation. As this quantity was used to account for seasonal and large day-to-day variations of solar heating, pyreheliometer measurements obtained from the nearest station having generally similar day-to-day weather conditions were assumed to be adequate. Examination of surface-weather maps and hourly sequence reports for each flight day indicated that data reported in the Monthly Weather Review (reference 4) for Nashville, Tenn., fulfilled these requirements. These pyreheliometer measurements give the total radiation (direct plus diffuse) received on a unit horizontal surface between sunrise and sunset.

The gust data obtained by the flight surveys consist of effective gust velocities obtained from instruments measuring airspeed, altitude, and acceleration as reported in reference 3. The data cover 23 flights on 19 days with approximately 3200 miles of flight in clear air at low altitudes and are considered sufficient for a preliminary analysis.

The meteorological conditions in the layer below the gradient wind level, the earth's friction layer, represent wind velocities ranging from zero to as much as 60 miles per hour, and friction-layer depths of from 1600 to 7000 feet. The friction layer was entirely clear of clouds for each flight although cloud forms other than thunderstorms or large cumulus were often present at higher altitudes. The lapse rate at flight time was not available. The 10:00 a.m. and the 4:00 p.m. data indicated, however, that the lapse rates were usually near the adiabatic with inverted and superadiabatic lapse rates probable in some instances.

METHODS OF EVALUATION AND RESULTS

Evaluation of the relation between measurements of the turbulence encountered by the airplane and the product combination of insolation and average wind shear requires the determination of values for the terms in the relation:

$$u \propto rv/h$$

where

u measure of observed turbulence

r total solar radiation received on a unit horizontal surface, gram calories per square centimeter per day

h depth of the friction layer, feet

v absolute magnitude of the vectorial difference between the anemometer and gradient wind velocities, feet per second

Meteorological Variables

The total daily solar radiation received on a unit horizontal surface was obtained directly from data published in the Monthly Weather Review. The average wind shear in the friction layer was determined for each flight by taking the upper limit of the friction layer as the first reported altitude at which the rawinsonde ascent indicated a discontinuity in the vertical lapse rate of temperature. The wind direction and velocity indicated by the rawinsonde reports for this altitude and that indicated by the anemometer records for the surface altitude were used to obtain the average wind shear at 10.00 a. m. Eastern Standard Time and at 4:00 p. m. Eastern Standard Time. The average wind shear in the friction layer for the period of each flight was then obtained on the basis of an assumed linear variation with respect to time. The values obtained for the total daily solar radiation r and the average wind shear v/h as well as the quantity rv/h are shown in table I for each flight.

The Measure of Observed Turbulence

The effective gust velocity, as defined in reference 5, was used as the basic measure of the vertical gustiness encountered by the airplane in flight. Figure 1 is an illustration of a method of presentation frequently used to describe the history of vertical gustiness in terms of this measure of turbulence. Each point in the figure was obtained by dividing the total miles of flight by the total number of gusts equal to or greater than given values of effective gust velocity. A line faired through these points provides a measure of turbulence by describing the gust history in terms of the average number of miles required to equal or exceed given values of effective gust velocity.

The gust history for each flight of the investigation was obtained by deriving the average flight miles required to equal or exceed given values of effective gust velocity. Inasmuch as the results obtained for individual flights indicate variations in both the slope and intercept of the faired lines, as illustrated in figure 1, two convenient points along the line were thought to be necessary to define adequately the intensity of turbulence encountered by the airplane. The effective gust velocities indicated by the faired lines for average distances of 1 and 10 miles were arbitrarily chosen to describe the gust history of each flight of the investigation. The effective gust velocity obtained for each flight for given distances of 1 mile U_{e_1} and that indicated for 10 miles $U_{e_{10}}$ are shown in table I.

Statistical Results

The relation between the meteorological quantity and the observed measure of turbulence was examined in accordance with standard statistical methods of correlation analysis as described in reference 6. The coefficients of correlation and other statistics pertinent to the investigation are given in the following table:

Coefficient of correlation between rv/h and U_{e_1}	0.88
Standard error of estimate of U_{e_1}	0.42
Standard deviation of U_{e_1}	0.88
Coefficient of correlation between rv/h and $U_{e_{10}}$	0.84
Standard error of estimate of $U_{e_{10}}$	0.80
Standard deviation of $U_{e_{10}}$	1.48

Regression lines of the observed measure of turbulence on the meteorological quantity are shown in figure 2 for U_{e_1} and $U_{e_{10}}$ as a function of the product rv/h. Also shown in figure 2 are lines indicating the limits for one standard error of estimate about the regression lines. Approximately two thirds of the observations may be expected to fall between these limits.

DISCUSSION

Consideration of the results presented in the previous section indicates that the coefficients of correlation between the quantity rv/h and the measures of observed turbulence are 0.88 and 0.84 for U_{e_1} and $U_{e_{10}}$, respectively. For samples of this size, the probability of obtaining correlation coefficients of these magnitudes between unrelated variables is of the order of 10^{-5}. The indicated relation between these variables, therefore, appears to be significant.

The effectiveness of the present relation for estimating turbulence intensities cannot be evaluated conclusively from the present data. Some measure of effectiveness may be obtained, however, from a comparison of the standard error of estimate about the regression lines with the standard deviation of the observed values of U_e. The standard errors of estimate of U_{e_1} and $U_{e_{10}}$ for the available-data sample are roughly one half of their respective standard deviations. The average error resulting from utilization of the relation to estimate turbulence intensities is therefore about one half that which would be expected if the average intensity of the turbulence were known and used as a basis of estimation.

The product form of relation was first suggested by a plot similar to figure 3 where the observed measure of turbulence U_{e_1} has been plotted as a function of the average wind shear v/h. When the observations are separated into periods corresponding roughly to late spring, fall, and winter, as shown in the figure, the observed turbulence for a given season varies directly with the intensity of wind shear as indicated by the faired lines. For short periods when the day-to-day variations of solar heating are small, the wind shear provides a measure of the turbulence intensity. The figure further indicates that, for given values of wind shear, the intensity of observed turbulence is greatest for warmer seasons and least for cooler seasons. This variation corresponds to the seasonal variations of solar heating.

The total daily solar radiation received on a unit horizontal surface was combined in the product form of relation to account for both the seasonal and large day-to-day variations in the intensity of solar heating. The high coefficients of correlation obtained between the product form of relation and the observed measures of turbulence, U_{e_1} and $U_{e_{10}}$, were obtained from data covering a relatively wide seasonal range of solar heating. The relation between the observed measure of turbulence and the product of total daily solar radiation with average wind shear in the friction layer would therefore appear to account for the seasonal and large day-to-day variations of turbulence during a two- or three-hour period beginning at noon local standard time. It should not, however, be expected to account for diurnal variations of turbulence.

The relation, $u \propto rv/h$, is of simple form and does not permit discrimination between variations in gust experience resulting from changes in flight altitude. Although the form of relation might be generally applicable to flights at other altitudes within the friction layer, the particular relations obtained in the form of the regression lines (fig. 2) are probably limited to flight altitudes and to topographical characteristics similar to those of the present investigation.

Variations of the gradient level and the height of the earth's surface with respect to the flight altitude might also be expected to cause variations in the observed gust experience. The gust data were therefore examined for differences in the gust experience over two portions of the course having approximately a 300-foot difference in surface elevation. The gust data were also examined for differences in gust experience associated with friction-layer depths. The data were separated into two groups based on friction-layer depths, the first for friction-layer depths less than 3000 feet, the second for friction-layer depths greater than 3000 feet. No significant differences in gust experience were distinguishable in either case. The variations of friction-layer depth and terrain features for the test data apparently had little effect on the observed gust experience.

CONCLUDING REMARKS

The quantity formed by the product combination of total daily solar radiation received on a unit horizontal surface with the average wind shear in the friction layer is shown to be related to the intensity of turbulence observed at low altitudes. Coefficients of correlation between this quantity and the effective gust velocities which were equalled or exceeded on the average of once in distances of 1 and 10 miles were 0.88 and 0.84, respectively. The relation between the quantity and turbulence intensity apparently accounts for seasonal variations. Because of the simplicity of form, however, the relation does not discriminate between differences in turbulence intensity resulting from variations of flight altitude or diurnal variations of turbulence. The significance of the relation when applied to regions having different surface roughness characteristics or when extended to other values of gust intensity has not been established and the lines of regression are limited to estimation of turbulence intensities for conditions similar to the test conditions.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

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TABLE I

SUMMARY OF GUST AND METEOROLOGICAL DATA

Date	Time (EST)	Gust velocity		Meteorological data		
		U_{e_1} (ft/sec)	$U_{e_{10}}$ (ft/sec)	r (g-cal/cm^2 day)	v/h (1/sec)	rv/h $\left(\frac{\text{g-cal}}{\text{cm}^2\text{day}}\right)\left(\frac{1}{\text{sec}}\right)$
Sept. 13, 1948	1:19 p. m.	6.8	10.7	275	6.52×10^{-3}	1.79
Sept. 13, 1948	3:28 p. m.	4.9	7.4	275	4.98	1.38
Sept. 14, 1948	12:40 p. m.	7.3	11.8	499	7.33	3.66
Sept. 27, 1948	1:48 p. m.	5.5	8.5	336	6.04	2.02
Sept. 30, 1948	1:46 p. m.	4.3	7.1	276	3.08	0.85
Oct. 9, 1948	12:40 p. m.	6.4	9.6	456	6.96	3.15
Oct. 13, 1948	1:07 p. m.	7.0	11.1	441	7.62	3.37
Oct. 13, 1948	3:12 p. m.	5.6	8.9	441	5.13	2.23
Oct. 18, 1948	1:49 p. m.	6.8	10.9	440	7.04	3.11
Nov. 17, 1948	12:06 p. m.	5.3	7.9	324	5.83	1.89
Nov. 17, 1948	2:47 p. m.	4.4	7.1	324	3.81	1.23
Nov. 20, 1948	11:35 a. m.	6.3	9.4	301	11.00	3.30
Nov. 24, 1948	11:29 a. m.	4.4	6.7	146	3.40	0.50
Nov. 30, 1948	10:17 a. m.	5.0	7.5	266	5.21	1.41
Dec. 6, 1948	2:21 p. m.	5.2	7.3	278	7.55	2.10
May 3, 1949	2:45 p. m.	5.3	8.2	695	2.64	1.83
May 4, 1949	2:45 p. m.	5.1	7.5	694	2.57	1.77
May 5, 1949	2:42 p. m.	5.8	9.0	658	2.93	1.92
May 6, 1949	1:35 p. m.	6.2	9.8	646	3.45	2.22
May 6, 1949	3:15 p. m.	6.0	9.1	646	2.93	1.89
May 12, 1949	2:27 p. m.	6.5	10.5	691	3.66	2.54
May 16, 1949	3:41 p. m.	5.4	8.0	458	2.82	1.29
May 19, 1949	11:30 a. m.	7.1	10.7	676	4.62	3.11

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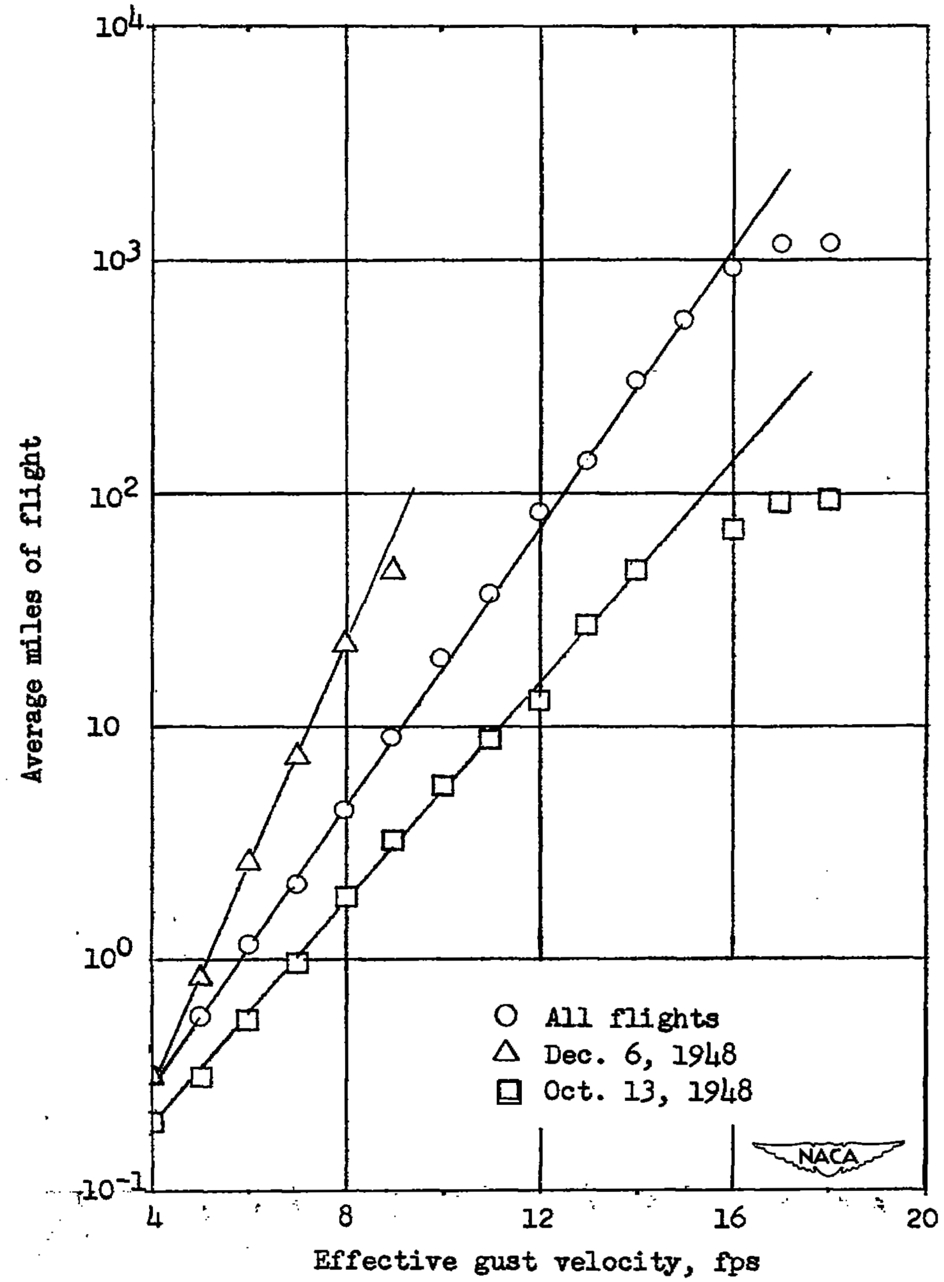

Figure 1.- Average miles of flight necessary to exceed given values of effective gust velocity in low-altitude clear-air turbulence.

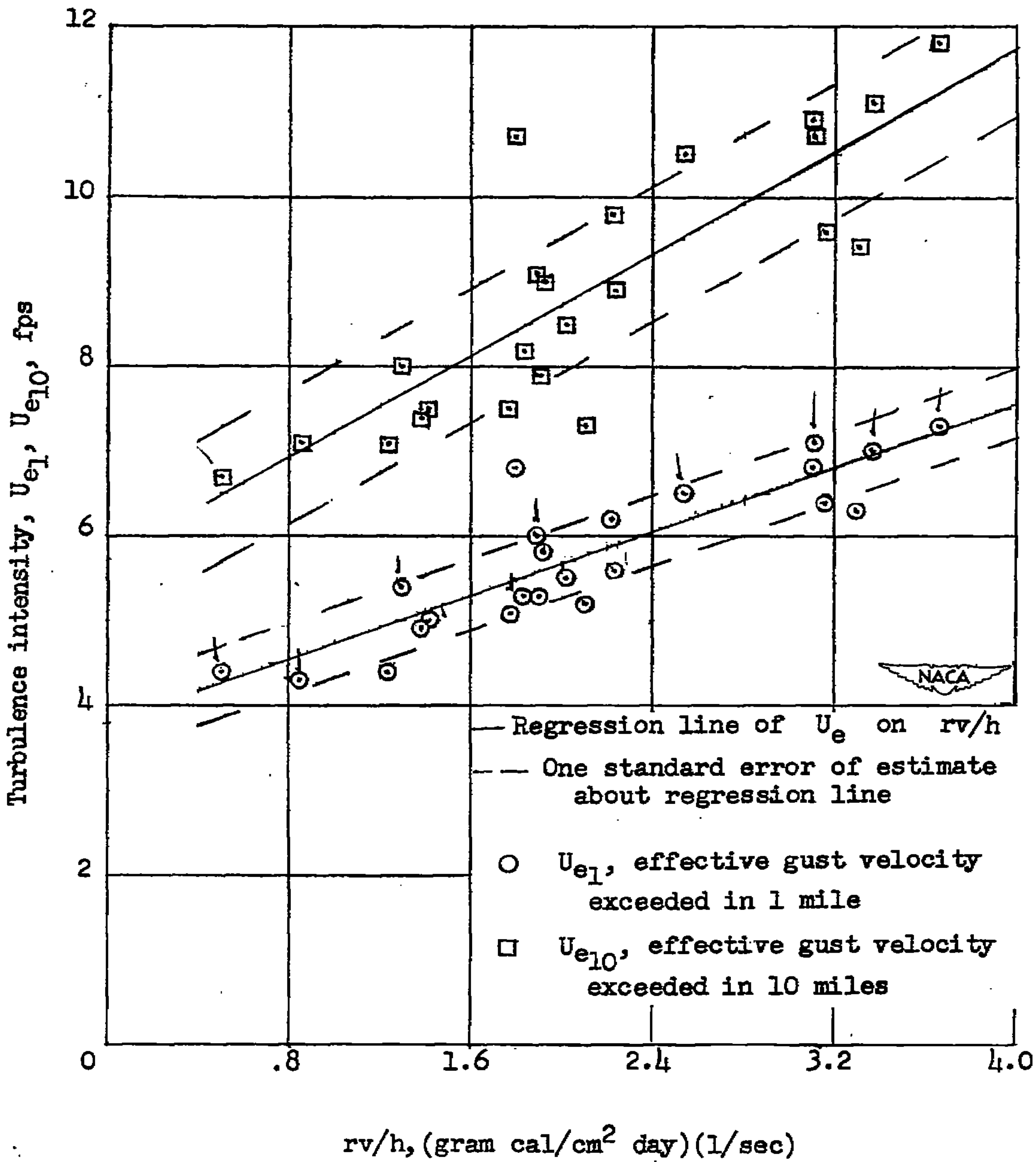

Figure 2.- Variation of turbulence intensity with insolation and wind shear.

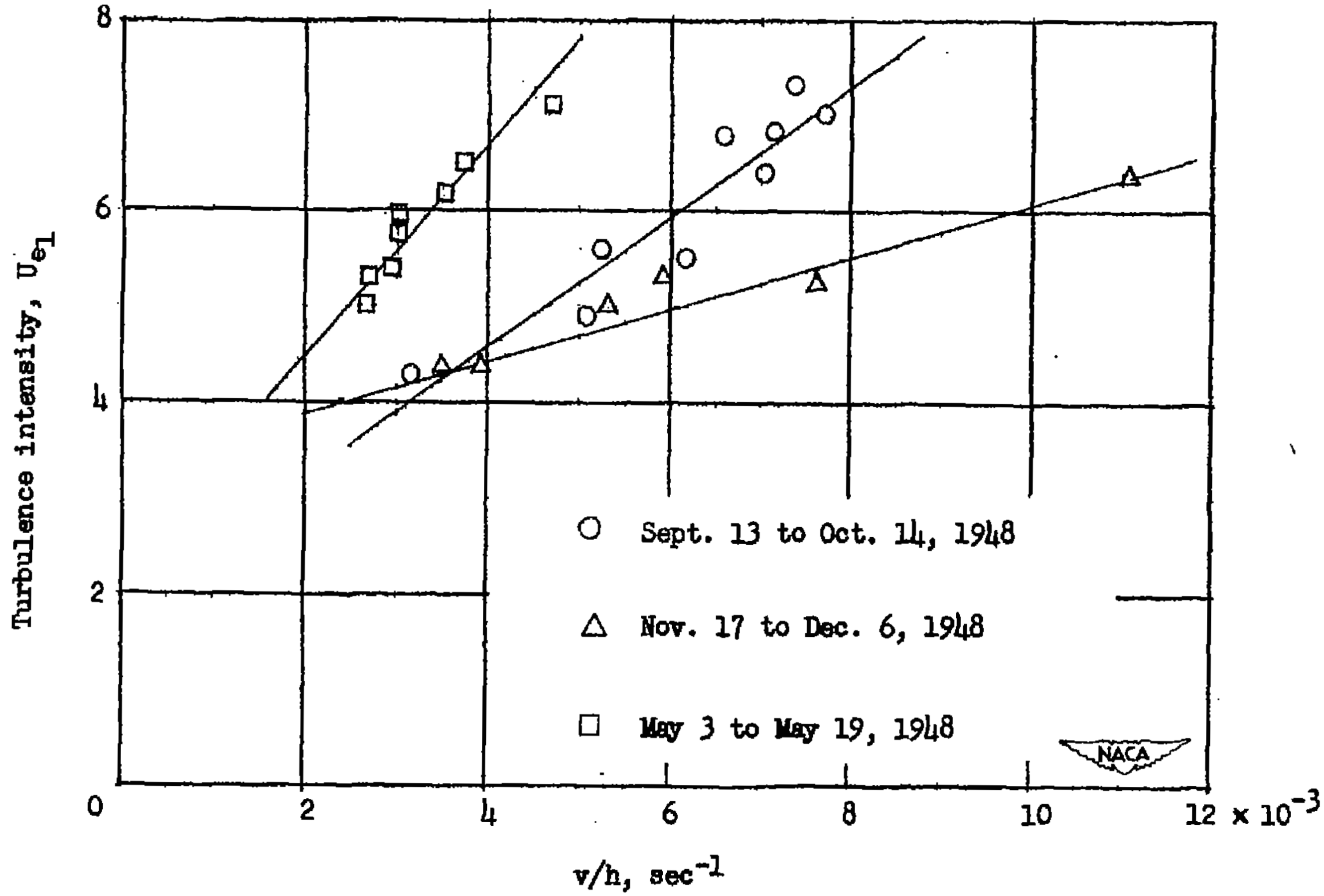

Figure 3.- Variation of turbulence intensity with average wind shear.